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13. ABSTRACT

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An improved Langmuir probe formula for modeling satellite interactions with near-geostationary environment

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Abstract. The Langmuir plasma probe model is an important tool in spacecraft current collection and charging calculations. In ideal geometries, such as a sphere or an infinitely long cylinder, the model is well understood. However, the realistic geometries of current collectors, or spacecraft, are nonideal. An empirical formula for a Langmuir probe with a given nonideal geometry would be useful. We derive such a formula for the SCATHA satellite by using the SC10 potential data obtained during electron beam emissions. The satellite rotated perpendicular to sunlight with the SC10 booms in the equatorial plane. We choose one special mode of operation during a quiet space environment. In this mode the beam current increased continuously, while the energy remained constant. We analyzed the variations of the vehicle potential responding to the unique driving factor, the beam current. To provide physical explanation to the behavior of the SC10 potential data, we model the interactions between the beam, photoelectron, and ambient currents. We present an algorithm which successfully yields an empirical Langmuir probe formula for SCATHA, from which we obtain improved estimate of ambient electron temperatures and densities. The results predicted by the improved Langmuir probe model compare favorably with the very few published measurements from the region.

1. Introduction

Ambient electrons and ions in space plasmas impact on the spacecraft. The surface potentials come to equilibria on timescales of milliseconds. The charging time is so short because spacecraft surface capacitances with respect to the space plasma are typically small. Some dielectric surfaces couple to subsurface materials. They may have higher capacitances and accordingly may take longer amounts of time to come to equilibria.

At equilibrium, a spacecraft behaves like a Langmuir plasma probe [*Mott-Smith and Langmuir*, 1926]. Since spacecraft are current collectors, their potentials are governed by the balance of currents as given in the Langmuir probe equation. The control of a spacecraft's potential differs from that of a laboratory Langmuir probe. In a laboratory, currents collected by Langmuir probes vary in response to the applied potential. In space, however, vehicle potentials float with respect to the ambient plasma. During charge-particle beam operations, a spacecraft's potential varies in response to the emitted current [*Lai*, 1989].

When the plasma density is high, the current density is limited by the Child-Langmuir's law. When the plasma density is low, such as at SCATHA altitudes (5–7 R_E), the current density from ambient plasma impacting on a spacecraft surface is not in the current-limiting regime. Instead, the current density is limited by the orbital angular momenta of the incoming charged particles. This, we refer to as the orbit-limited regime.

In the orbit-limited regime, the Langmuir probe equation [*Mott-Smith and Langmuir*, 1926] for a positively charged probe is

$$\mu I_e(0)\left(1 - \frac{q_e\phi}{kT}\right)^\alpha - + I_i(0)\exp\left(-\frac{q_i\phi}{kT}\right) = 0 \qquad (1)$$

for $e\phi > kT$. In (1), $I_e(\phi)$ and $I_i(\phi)$ are the electron and ion currents, respectively, which are collected from the local plasma by a probe charged to a potential ϕ relative to the plasma, and T is the plasma temperature. In (1), $q_e = -e$, and $q_i = e$, where e is the magnitude of the elementary charge. The multiplicative factor μ is unity if the probe is a perfect sphere and $2/\pi^{1/2}$ ($\approx$1.1) if it is an infinite cylinder; the power factor α in (1) is unity and 1/2 respectively. Since the geometry of the probe is neither a sphere nor an infinitely long cylinder, μ and α have neither value.

Laframboise and Parker [1973] generalize the concept of orbit-limited motion to include spheroids. They conclude that prolate and oblate spheroids have an orbit limitation in the Laplace limit as long as the major-to-minor axis ratios are less than 1.653 and 2.537, respectively. They do not give α values for specific ratios. Moreover, SCATHA is not a spheroid. Thus their work is not directly applicable here.

Equation (1) describes a balance in which the total current to the probe equals zero. When other currents are involved, (1) must be modified accordingly. For example, if there are currents due to secondary electrons I_s, artificial beam emissions I_b, and photoemissions I_{ph} due to sunlight, these terms have to be included:

$$\mu I_e(0)\left(1 + \frac{e\phi}{kT}\right)^\alpha - I_i\exp\left(-\frac{e\phi}{kT}\right) = I_b + I_{ph} + I_s \qquad (2)$$

The magnetic field (~100 nT) at SCATHA altitudes is weak. $\mathbf{V} \times \mathbf{B}$ electric fields are negligible since they are much

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weaker than sheath fields. Also, at such altitudes, the ambient ion currents are typically an order of magnitude smaller than electron currents [*Reagan et al.*, 1981] and are unimportant unless the spacecraft is charged negatively to thousands of volts.

The Langmuir probe equation is often used in spacecraft-charging calculations. In the literature, α is commonly taken as 1 for satellites bearing some resemblance to spheres. The main objective in this paper is to obtain an improved Langmuir probe formula for the SCATHA satellite by determining the value of α. Toward this end, we must first identify and estimate the various currents.

We choose to study the SCATHA satellite measurements taken in the period 2033 to 2050 UT on March 11, 1981. The altitude was 42,600 km, and the local time was near 0500. This day is chosen because of the following reasons. The ambient environment was quiet (not stormy) and steady; the 24-hour sum of 3-hour *Kp* indices was 14- [*Coffee*, 1981]. During the period considered, an electron beam was emitted from the satellite. The beam current exceeded the ambient current intercepted by the satellite. Therefore the spacecraft potential was controlled by the electron beam emission. Furthermore, the beam current was continuous, and the level of spacecraft charging was positive, in the range 0 to +170 V. The ion current can be ignored under these circumstances.

In section 2, we describe the SCATHA satellite and the SC10 instrumentation on board. The general characteristics of the oscillations of SC10 voltage measurements and the observations on March 11, 1981, are described in section 3. To study in detail the oscillation behavior on March 11, 1981, we present our theory in subsections 4.1, 4.2, and 4.3. In subsection 4.1, we model the photoelectron currents originating from the boom surfaces and flowing toward the satellite body. By using the measurements obtained, we determine the photoemissivity of copper-beryllium, the surface material on the outer segment of the booms. In section 4.2 we delineate three interaction regimes depending on the contribution of various currents to the satellite potential. In section 4.3 we choose the appropriate regime in which α is the only parameter to be determined, and we present an algorithm for calculating α. With α determined, we have at hand an improved Langmuir probe formula for SCATHA. Applying this formula to the current-voltage measurements, we obtain the local plasma temperature and density. Finally, in section 5, we summarize the main findings of this paper and compare our plasma results with published ones obtained with different instrumentation and techniques under comparable environmental conditions.

2. SCATHA Satellite

SCATHA was launched in January 1979, to investigate natural and artificial processes controlling charging at high altitudes. Descriptions of the experiments on SCATHA are given by *Fennell* [1982]. The satellite is about 1 m long and 1.6 m in diameter. It rotates about once per minute with a spin axis perpendicular to the Sun-Earth line. SCATHA is equipped with two 50-m booms (SC10) that are electrically isolated from the satellite ground. The surface material of the outer 20 m of each boom is made of an exposed copper beryllium (CuBe) wire. The inner segment is coated with kapton, an insulating material. The SC10 potential ϕ represents the difference between the potential ϕ_{CuBe} of the tip of a boom and that ϕ_s of the satellite ground [*Lai et al.*, 1986]. That is,

$$\phi = \phi_{CuBe} - \phi_s. \tag{3}$$

An electron beam (SC4-1) could be emitted from SCATHA with various energies and currents. During quiet days in sunlight, SCATHA normally charges positively to a few volts. The emission of an electron beam tends to raise the satellite potential to a degree that depends on ambient conditions as well as beam energies and currents. When the satellite rotates in sunlight, the amount of solar illumination on boom surfaces varies sinusoidally, as does the photoelectron current from the booms to the spacecraft.

When SCATHA is in sunlight, with or without beam emission, SC10 potentials show oscillations at twice the satellite rotation frequency [*Lai et al.*, 1986, 1987]. When the satellite enters eclipse, the amplitude of oscillation decreases gradually; this evidence supports the contention that the oscillation is due to the effects of photoelectrons.

When SCATHA charged positively as a result of electron-beam emissions, photoelectrons from the booms were attracted back toward the satellite body [*Lai et al.*, 1987]. The booms form part of the satellite body's electrical environment. In this case, the satellite body not only interacts with its ambient plasma environment but also with the booms (Figure 1).

Because of the high secondary-emission coefficient of CuBe, the outer sections of the SC10 booms should not charge to high negative potentials, except in unusually energetic plasma environments [*Lai*, 1991]. On quiet days, the potential ϕ_{CuBe} on SCATHA typically varies within ± 5V [*Lai et al.*, 1986]. When the spacecraft potential ϕ_s is high compared with ϕ_{CuBe}, ϕ (3) represents a good approximation of the spacecraft potential ϕ_s with the sign reversed, that is, $\phi \approx -\phi_s$. There are several instruments for measuring spacecraft potential on SCATHA [*Fennell*, 1982]. They confirm that SC10 often provided good approximate measurements of the satellite potential. We assume that SC10 measured $\phi \approx -\phi_s$, where ϕ_s was of several tens of volts and was controlled by electron beam emissions.

3. Observations

We describe in this section the general characteristics of SC10 potential oscillations and the specific behavior of the oscillations on March 11, 1981.

3.1. General Characteristics

In sunlight, as the electron beam current increases from low values, the spacecraft potential increases. Furthermore, not only the maxima $|\max(\phi)|$ of the SC10 potential in an oscillation period but also the amplitude $|\max(\phi) - \min(\phi)|$ of oscillation increases. The extrema of the oscillation correlate well with the Sun angle of the booms [*Lai et al.*, 1987]. Minima occur at $\theta = 0°$ and $\theta = 180°$ and maxima at 90° and 270°. Another instrument, SC2, also measured the potential of the spacecraft body. While still in operation, the oscillation frequency and phase of SC2 potential were identical with those of SC10 during electron beam emissions. This indicates that the oscillations are due to the variations of ϕ_s.

In the rest of this section, we discuss three points on the SC10 potential data. The first one concerns whether the

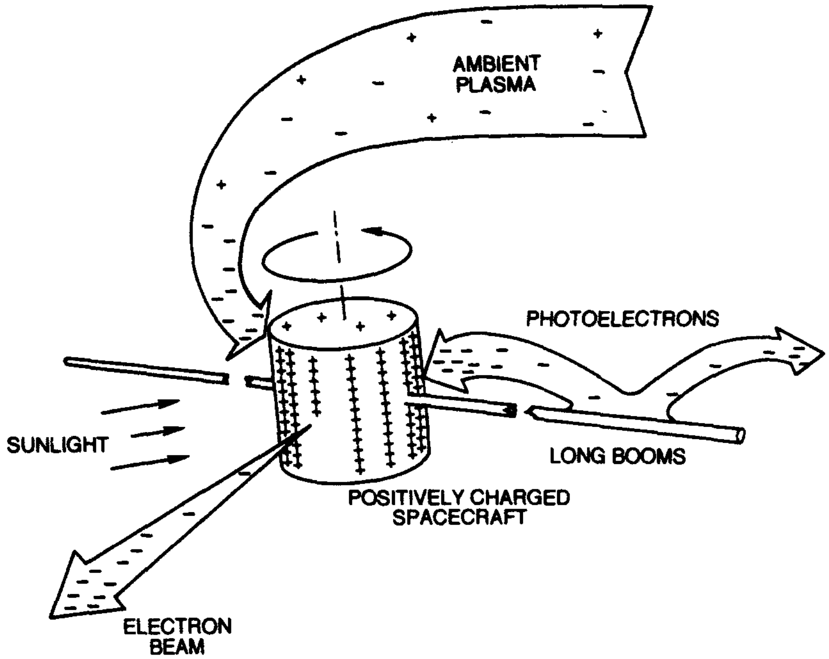

Figure 1. Schematic diagram of the SCATHA satellite with beam emission.

boom (SC2 or SC10) potential oscillations always depend on vehicle potential modulation. The answer to this question is "no" under two extreme conditions of vehicle charging. In the first extreme, the vehicle potential relative to the space plasma is a few volts, and is nearly constant, as during quiet days in sunlight without beam emission. The booms may also be at a few volts relative to the space plasma. Under this condition, there is a twice per rotation modulation of the boom potentials. Such a modulation has been identified to be due to photoemission from the booms [*Lai et al.*, 1986; *Craven et al.*, 1987]. In the other extreme, the space plasma is so energetic and unusual that both the vehicle and the booms are charged to high potentials (a few kilovolts). This condition is rare [see *Lai*, 1991*a*, *b*] and did not occur on quiet days.

The second point to discuss concerns the use of SC10 rather than other measurements (SC2, SC5, and SC9) of vehicle potential on SCATHA. All measurements were approximate. Because of the short length (3 m) of its boom, the SC2 data were not accurate for measuring vehicle potential relative to the space plasma. The SC2 instrument failed early in 1979. The SC5 data below about 100 eV were inaccurate. The SC9 data, which measured vehicle potential by identifying the shift of the ambient electron distribution, were also inaccurate at low potentials and, besides, were sampled at a slow rate (once per 16 s).

The third point concerns the accuracy of SC10 data in representing the vehicle potential. At high-vehicle potentials, the Coulomb potential sheath may extend far beyond the 50-m booms, the data would merely reflect the potential difference between the vehicle and a point inside the sheath. For potentials below about 300 V, the error due to the Coulomb sheath is negligible.

3.2. Satellite Potential Oscillations

Figure 2 presents data acquired on March 11, 1981. The beam energy was constant at 300 eV. The beam current increased continuously from near zero to about 90 μA. There are several 30-s periods of calibration dropouts. Data taken during such periods are ignored in our study. Oscillations in the potential of SC10 detected on March 11, 1981, correlate with boom-Sun angle θ, with spacecraft potential

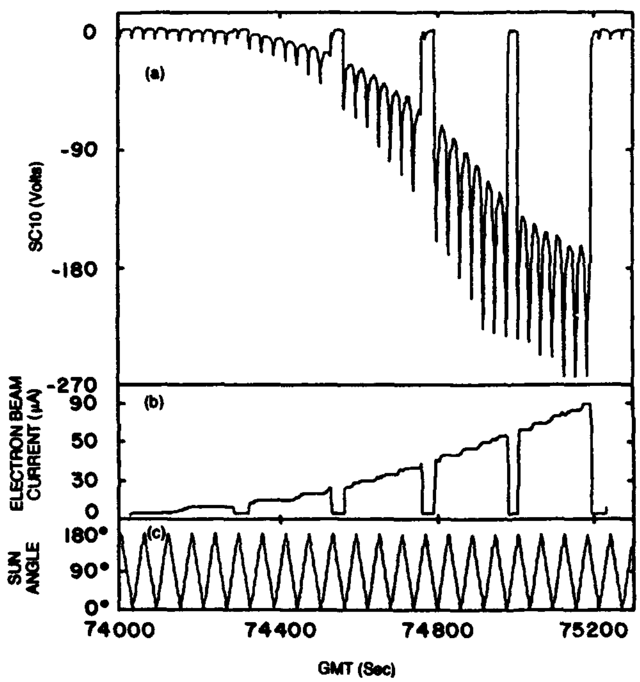

Figure 2. March 11, 1981, measurements on SCATHA. (*a*) SC10 ϕ potential in volts, (*b*) electron beam current I_b in microamperes, and (*c*) SC10 boom Sun angle θ in degrees are presented as functions of time. The electron beam energy is 300 eV. The dropouts at regular intervals are for calibration.

maxima occurring when the booms were parallel or antiparallel to sunlight direction and minima when the booms were perpendicular to it. Starting from zero beam current, the potential oscillation amplitude increased monotonically with beam current until a critical level of about 60 μA was reached. The amplitude decreased slightly with further increases in beam current.

4. Discussion

To provide a physical interpretation of these observations, we model the photoelectron current flowing towards the satellite body from the SC10 booms and delineate various regimes of interactions. We then provide an algorithm for determining the exponent α in the Langmuir probe equation (1).

4.1. Photoelectron Current Modeling

The photoelectron current $I_{ph}(\phi_s, \theta)$ from the booms is a function of the Sun angle θ. Depending on the potential ϕ_s of the satellite body, some fraction f of this current flows to the main body of the spacecraft. The satellite potential ϕ_s depends in a self-consistent manner on the photoelectron current $I_{ph}(\phi, \theta)$ received from the booms. In the low-density plasmas at SCATHA altitudes, the orbit-limited Langmuir plasma probe model applies for the collection of ambient currents. The current-balance equation for the satellite body is

$$\mu I_e(0)\left(1 + \frac{e\phi}{kT}\right)^{\alpha} + I_{ph}(\phi_s, \theta) = I_b(\phi_s) - I_r(\phi_s) \tag{4}$$

where

$$I_{ph}(\phi, \theta) = 2d \int_0^{50\text{ m}} dr\, f[\phi(r)] j_{ph} \sin\theta \tag{5}$$

and d is the boom diameter $I_e(0)$ is the ambient current collected if the spacecraft potential ϕ_s is zero with no photoelectron or beam emissions. I_b is the emitted electron beam current. If the beam's energy is high and its current density low, all beam particles escape. However, if the beam's energy is low and its current density is high, some beam particles return and the return current I_r becomes nonzero.

For a spherical body, the power α of the orbit-limited current collection term in (1) equals unity; for an infinite cylinder, α equals 1/2. However, the SCATHA satellite is neither a sphere nor a long cylinder. Rather, it has a short cylindrical shape with nearly the same length and diameter. Thus the power α for SCATHA has neither value, and it may fall between them.

To model the photoelectron current $I_{ph}(\phi)$ from the booms to the satellite, we assume a photoelectron energy spectrum and a satellite sheath potential profile $\phi(r)$ as a function of distance r from the satellite surface. Both laboratory and space experiments have shown that a Maxwellian distribution is a good approximation for describing the photoelectron energy spectrum [*Hinteregger et al.*, 1965; *Whipple*, 1981]. The photoemissivity j_{ph} of the copper-beryllium boom surface material on a rotating satellite has been estimated to be between 2×10^{-9} and 4×10^{-9} A cm^{-2} [*Kellogg*, 1980]. In this paper, we regard j_{ph} as a parameter to be determined

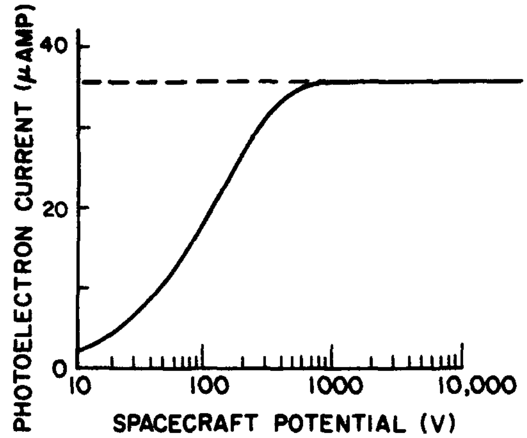

Figure 3. Total photoelectron current $I_{ph}(\phi_s, 90°)$ (equation (6)) arriving at the spacecraft body as a function of spacecraft potential ϕ_s. The photoemissivity j_{ph} used is 3.5 nA cm^{-2} (equation (5)).

in (5). The calculated value of j_{ph} is then compared with Kellogg's result.

We next consider the photoelectrons generated on a boom surface element at distance r from the main body of the spacecraft. Some fraction f of the photoelectron current moves toward the satellite with the rest escaping. The partition of photoelectron current depends on the energies of the photoelectrons and the sheath potential $\phi(r)$ at r. In this model the fraction f is given by [*Lai et al.*, 1987]

$$f[\phi(r)] = \frac{\int_0^{e\phi(r)} dE\, E \exp(-E/kT_{ph})}{\int_0^{\infty} dE\, E \exp(-E/kT_{ph})} \tag{6}$$

where the satellite sheath potential $\phi(r)$ is modeled using the Debye form [*Whipple et al.*, 1974]:

$$\phi(r) = \phi(0) \frac{R}{r + R} \exp(-r/\lambda_D) \tag{7}$$

Here R is the radius of the satellite body, and λ_D is the Debye distance. For SCATHA environments, we assume that the Debye length λ_D of the ambient plasma is about 45 m [*Aggson et al.*, 1983], and the photoelectron temperature T_{ph} is about 2 eV [*Whipple*, 1981; *Lai et al.*, 1986]. Using this model, we have computed the photoelectron current $I_{ph}(\phi, 90°)$ going toward the satellite body. The results appear in Figure 3.

The maxima and minima of the SC10 potential difference measurements of Figure 2, plotted in Figure 4, display the emitted beam currents as functions of the satellite potential. Data with photoemission (min $|\phi|$ with $\theta = 90°$ or 270°) from the booms are plotted in Figure 5*a*, and those without photoemissions (max $|\phi|$ with $\theta = 0$ or 180°) are plotted in Figure 5*b*. At low-beam currents, each set of current-voltage data varies smoothly. The measurement trend suddenly deviates from the trend line at a critical current. Without photoemission, the critical current is about 60 μA with the spacecraft potential at about 220 V. With photoemission, the

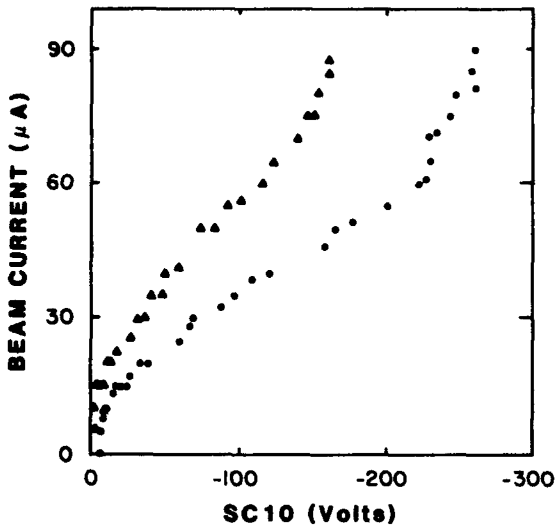

Figure 4. The maxima and minima of SC10 potential ϕ (from Figure 2) as functions of emitted beam current.

critical current is about 70 μA with the spacecraft at a potential of about 140 V.

The total photoelectron current $I_{ph}(\phi, 90°)$ is computed for a given value of photoemissivity j_{ph} using (5) and (6). This computed total photoelectron current $I_{ph}(\phi, 90°)$ is then added to the current in the maximum $|\phi|$ (θ = 0 or 180°) curve, which represents the spacecraft body potential when there is no photoelectron current from the booms to the spacecraft body. The result of this addition should represent the current collection of the satellite body during maximum sunlit conditions at the booms, that is, during $|\phi|$ min (θ = 90° or 270°). We find that the obtained curve fits best with the experimental data points of min $|\phi|$ when the value of the photoemissivity j_{ph} (5) is about 3.5 × 10^{-9} A cm^{-2} (Figure 6). This value of j_{ph} determined for the CuBe surfaces on the SC10 booms of SCATHA agrees with that (between 2 × 10^{-9} and 4 × 10^{-9} A cm^{-2}) estimated by *Kellogg* [1980] for the CuBe surfaces on the Helios spacecraft.

4.2. Interaction Regimes

The satellite potential $\phi_s(\theta)$ oscillates as the satellite and booms rotate in sunlight. The amplitude of the potential oscillation is given by $\Delta\phi = \phi_s(\theta = 0 \text{ or } 180°) - \phi_s(\theta = 90° \text{ or } 270°)$. As the beam current I_b increases, so does the $\Delta\phi$. When the satellite charges to near beam potential, the beam current does not escape completely [*Olsen*, 1989].

Three regimes of interactions 1, 2, and 3 can be identified in cases with and without photoemission (Figures 5*a* and 5*b*). In regime 1 and 2, the I_b is unsaturated, and the return current I_r is zero. In regime 1, some photoelectrons from the satellite body escape because the satellite positive potential ϕ_s is low. The amount of photoelectron current leaving the satellite body is a function of satellite potential ϕ_s. In our model the current balance equation is

$$\mu I_e(0)\left(1 + \frac{e\phi}{kT}\right)^{\alpha} + I_{ph}(\phi_s, \theta) = I_b(\phi_s) + J_{ph}(\phi_s, \theta) \quad (8)$$

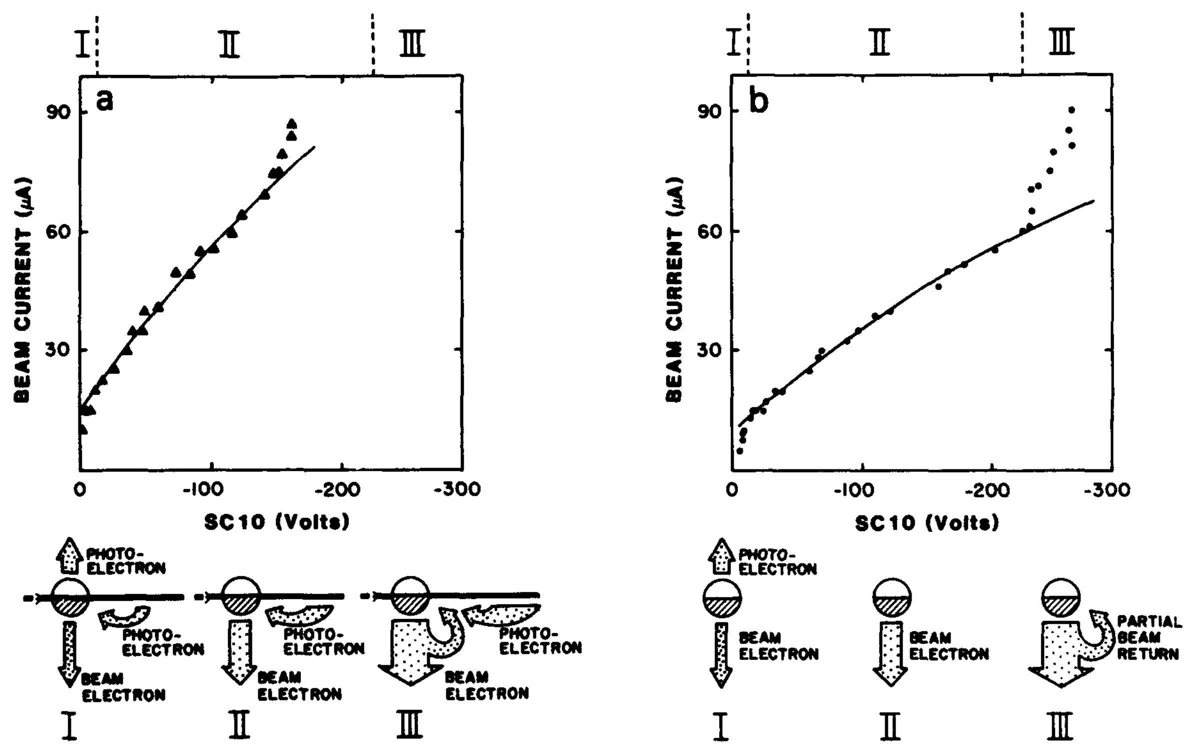

Figure 5. (*a*) The emitted beam current I_b and the SC10 potential with photoemission (minimum $|\phi|$ with θ = 90° or 270°). (*b*) The emitted beam current I_b and the SC10 potential ϕ without photoemission (maximum $|\phi|$ with θ = 0 or 180°). The three regimes in each case, Figure 5*a* or 5*b*, are discussed in the text. The cartoons below the *x* axis show schematically the physical processes in the regimes.

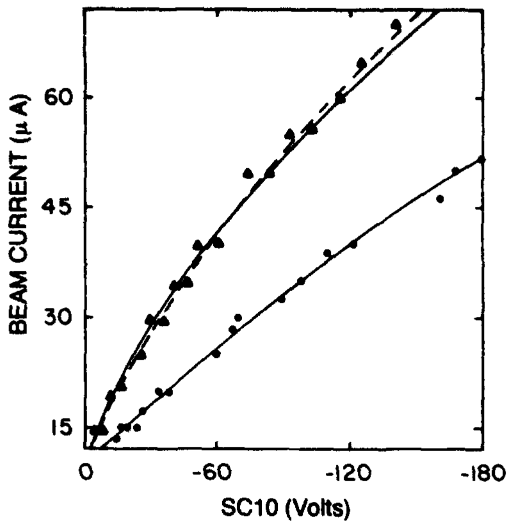

Figure 6. Fits to determine the photoelectron current. The lowest curve is a polynomial fit. The difference between the two data sets shown in Figure 4 is fitted by using (5). The upper solid curve is obtained by using $\lambda_D = 45$ m and $j_{ph} = 3.5$ nA cm^{-2} and the dash curve $\lambda_D = 12$ m and $j_{ph} = 6.5$ nA cm^{-2}.

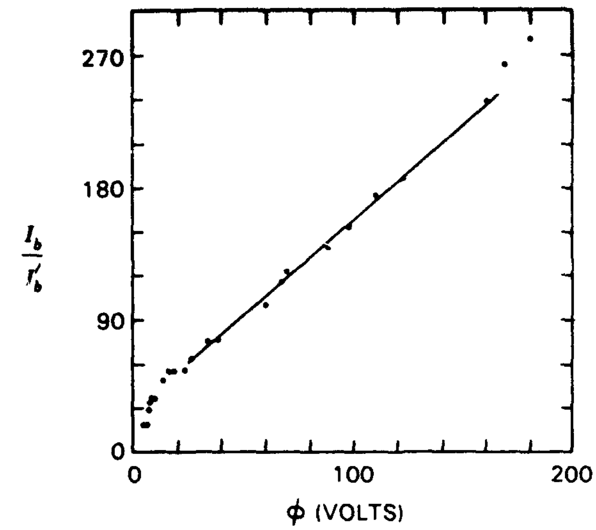

Figure 7. Solutions to (12) to determine the parameter α.

where $J_{ph}(\phi_s, \theta)$ is the photoelectron current leaving the satellite body.

In regime 2, the photoelectron current from the satellite body is very small because the satellite body potential energy $e\phi_s$ is high compared with the photoelectron energy:

$$\mu I_e(0)\left(1+\frac{e\phi}{kT}\right)^{\alpha}+I_{ph}(\phi_s,\theta)=I_b(\phi_s) \tag{9}$$

By extrapolation [*Gonfalone et al.*, 1979], the regime 2 curve intercepts the y axis ($\phi_s = 0$) at about 10 μA (Figure 5*b*). This determines $\mu I_e(0)$ to be approximately 10 μA in (4) which gives $I_b(0) = \mu I_e(0) \approx 10$ μA at the intercept. Using the surface area $D \approx 9.05$ m^2 of SCATHA and the average ambient current density $J_e \approx 0.115 \pm 0.10$ nA cm^{-2} obtained in a 45 days average in 1979 at SCATHA altitudes [*Purvis et al.*, 1984], one obtains a result for the average current intercepted by SCATHA as $DJ_e \approx 10.4 \pm 9.1 \times 10^{-6}$ A if $\mu = 1$ or $9.5 \pm 8.3 \times 10^{-6}$ A if $\mu = 1.1$. This average result is of the same order of magnitude as the $I_e(0)$ determined ($\approx$10 μA), the ambient current intercepted by SCATHA on March 11, 1981.

In regime 1, the data points deviate from the curve extrapolated from regime 2, because of photoelectrons leaving the spacecraft body. On the other hand, very few of the photoelectrons from the booms can reach the spacecraft body, because of the low attraction offered by ϕ_s. In regime 2, a multibody interaction occurs between the satellite body, the booms, the electron beam, and the ambient plasma. This regime will be discussed further in section 4.3. In regime 3, beam saturation occurs, and part of the beam current returns; this regime is not of main interest here. Physical processes characteristic of the three regimes are shown schematically at the bottoms of Figures 5*a* and 5*b*.

4.3. An Algorithm for Determining α

We now offer an algorithm for determining the value of power factor α (1). When there is no photoemission in regime 2 (Figure 5*b*), the only currents involved are the ambient electron and ion currents and the beam current I_b. Secondary electrons have insufficient energy to escape, since the $\phi_s > +30$ V. Furthermore, neither photoelectron current I_{ph} nor beam return current I_r is involved in this regime. The beam current I_b provides the driving force; the response ϕ is then a function of I_b only. Unlike I_{ph} and I_r, the beam current I_b is controlled and therefore known.

$$\mu I_e(0)\left(1+\frac{e\phi}{kT}\right)^{\alpha}=I_b \tag{10}$$

Differentiating (10) by $e\phi$ gives

$$I_b'(e\phi)=\frac{\alpha\mu}{kT}I_e(0)\left(1+\frac{e\phi}{kT}\right)^{\alpha-1} \tag{11}$$

where I_b' denotes differentiation of I_b by $e\phi$. Dividing (10) by (11), we obtain

$$\frac{I_b}{I_b'}=\frac{1}{\alpha}(kT+e\phi). \tag{12}$$

Equation (12) is a simple formula enabling α and kT to be determined. If the data $I_b(\phi)$ satisfy the Langmuir probe equation (10), they should satisfy (12). An algorithm based on (12) is as follows. Plotting the data I_b/I_b' as a function (ordinate) of $e\phi$ (abscissa) should yield a straight line with $1/\alpha$ as the slope. Once α is determined, the ambient electron temperature T can be determined from the intercept (at $e\phi = 0$) which equals kT/α.

Using data from Figure 5*b*, Figure 7 shows a plot of I_b/I_b' as a function of $e\phi$. In Figure 7 the data I_b/I_b' falls into a straight line for the potential range from $\phi \approx$ 25–160 V. This linear dependence of I_b/I_b' on $e\phi$ is as predicted by (12). Outside this range, the current-voltage behavior deviates from the simple Langmuir probe equation given by (10). Below $\phi \approx 20$ V, some secondary electrons and photoelec-

trons from the spacecraft body escape, and above $\phi \approx 160$ V, some beam electrons return. Between the two critical values of potential ϕ, I_b/I'_b falls on a straight line, as predicted by (12). From the slope of this line, we obtain the power factor $\alpha = 0.774$. This fitted value of α lies about halfway between the values for a sphere and an infinitely long cylinder.

After obtaining α, one can obtain the ambient electron temperature kT from the intercept in Figure 7. The intercept equals kT/α and gives $kT \approx 23.2$ eV. This value is comparable to $kT \approx 64$ eV [*Whipple*, 1981] which was measured by a different method on the ATS-5 satellite. Since the environment (e.g., plasma sheet and plasmasphere) is unknown, the comparison is not meant to be strict. We merely note that the measurements are of the same order of magnitude.

Taking $kT \approx 23.2$ eV and the ambient current $I_e(\phi = 0) \approx 10$ μA obtained from the intercept (section 5), we can determine the ambient electron density n_e by the following equation:

$$I_e(0) = \frac{1}{4} n_e e V_e D = \frac{e n_e D}{4} \left(\frac{8kT}{\pi m}\right)^{1/2} \approx 10 \mu A \quad (13)$$

which gives $n_e \approx 8.47$ cm^{-3} for $\mu = 1$ and 7.70 for $\mu = 1.1$. We cannot determine μ without knowing $I_e(0)$ independently.

5. Summary and Conclusions

The equilibrium potential of a spacecraft is governed by current balance as given in the Langmuir probe equation. The power α in the Langmuir probe equation [*Mott-Smith and Langmuir*, 1926] is well known to be 1 or 1/2 for a spherical or infinitely long cylindrical probe, respectively. For most spacecraft, the geometry is neither a sphere nor an infinite cylinder. For improved spacecraft charging modeling, it is better to determine and use the correct value of α rather than taking $\alpha = 1$ as commonly practiced. This leads to a lower estimate of kT and a higher estimate of the plasma density.

With beam emissions, the beam current emitted is likely known except when there is beam return. From current-potential measurements, it is then possible to deduce the value of α. Before one can apply an algorithm to deduce the power α, one has to identify and disentangle all the various interactions between the spacecraft body, the booms, the ambient plasma, and the beam emitted or even returned. We have taken the March 11, 1981, current-voltage measurements obtained on SCATHA satellite for a case study. The day was chosen because there was no storm and the period chosen was the only one in which the SCATHA electron beam current was increasing continuously instead of changing in large steps.

5.1. Key Observations

The SC10 potential difference measurements oscillated at twice the satellite frequency with their maxima occurring when the booms were parallel or antiparallel to sunlight ($\theta = 0°$ or $180°$) and the minima occurring when the booms were perpendicular. The amplitude of oscillation increased with the beam current until the satellite potential was near the beam energy.

5.2. Key Interpretations

When the booms were aligned with sunlight, there was no photoemission emitted from the boom surfaces. When the booms were perpendicular to sunlight, the photoemission from the booms was maximum. As the emitted beam current increased, the spacecraft potential increased. As a result, the spacecraft sheath engulfed part of the booms, and therefore some photoelectrons from the booms were attracted toward the satellite body. The amount of photoelectron current, and therefore the amplitude of oscillation, increased with the spacecraft potential. When the spacecraft potential was near the beam energy, the beam partially returned. We have identified three different interaction regimes (Figure 5). In regime 1, photoelectrons were emitted from the spacecraft body. Also, in this regime, the approximation $\phi = -\phi_s$ may not be accurate. In regime 3, partial beam return occurred. In between these two regimes, we have modeled the interactions.

5.3. Calculations and Results

1. Using a simple photoelectron current partition model to fit the measured oscillation amplitude, we found that the photoemissivity j_{ph} of the boom surface was about 3.5×10^{-9} A cm^{-2}.

2. The ambient current $I(0)$ can be deduced by extrapolating the regime 2 curve to intercept the $\phi = 0$ axis. From the intercept, we obtained the ambient current $I(0)$ intercepted by SCATHA as 10 μA.

3. For Langmuir probe modeling, we chose the current-voltage measurements in regime 2, when the booms were aligned with sunlight. No photoemission from the booms was involved with these measurements. No partial beam return occurred in this regime. The spacecraft potential ϕ was a function of the beam current I_b, the ambient current $I(0)$, and the ambient temperature T_e only (10). We plotted I_b/I'_b as a function of ϕ. The slope gives α and the intercept kT_e/α. With α, kT_e, and $I(0)$ known, we can deduce the ambient electron density n_e. The results obtained are $\alpha \approx 0.774$, $kT_e \approx 23.2$ eV, and $n_e \approx 8.47$ cm^{-3} for $\mu = 1$ or $n_e \approx 7.70$ for $\mu = 1.1$.

5.4. Comparisons With Other Measurements

The calculated photoemissivity result agrees with the measurements by *Kellogg* [1980]. The ambient current value obtained agrees with the statistical measurements of *Purvis et al.* [1984]. It is interesting that the value of $\alpha \approx 0.774$ lies between the two known values 1 and 1/2, corresponding to a perfect sphere and an infinite cylinder, respectively. Since the geometry of SCATHA resembles a short cylinder, the α result seems reasonable. The ambient temperature kT_e is comparable to the value $kT_e \approx 64$ eV obtained on ATS-5 [*Whipple*, 1981] at the geosynchronous environment by means of different instrumentation and technique. Since the environment is unknown, we merely note that our result, $kT_e \approx 23$ eV, is not unreasonable for near geosynchronous orbit, on a quiet day near local dawn, at 5.5 R_E (perigee for SCATHA).

We compare our n_e result with the statistical results of GEOS measurements obtained by means of relaxation sounding at 6.6 R_E [*Higel and Lei*, 1984]. During the period considered, the altitude of SCATHA was approximately 40000 km ($\approx$7.3 R_E) at 0500 LT and the ΣKp was 14−. At

the nearest values of ΣKp, the GEOS plasma densities at 6.6 R_E and 0500 LT were about 3 to 7 cm^{-3} for $\Sigma Kp = 13$, 1 to 2 cm^{-3} for $\Sigma Kp = 15$, and 8 to 9 cm^{-3} for $\Sigma Kp = 21$ [see *Higel and Lei*, 1984, Figures 3E, 3A, 3B]. In this comparison, our local plasma density n_e is on the high side.

5.5. Final Comments

We have assumed a Debye length $\lambda_D = 45$ m [*Aggson et al.*, 1983] to fit for the photoelectron current (top solid line in Figure 6). In retrospect, we use $\lambda_D = 12$ m ($kT_e \approx 23.2$ eV and $n_e \approx 7$ cm^{-3}) to fit (dashed line in Figure 6), yielding $j_{ph} \approx 6.5 \times 10^{-9}$ amp cm^{-2}. This photoemissivity value j_{ph} is higher than *Kellogg*'s [1980] estimate.

In our algorithm (12) we have avoided any photoelectron current flowing from the booms to the vehicle body by selecting the branch of SC10 potential data points (Figure 4) with Sun angle $\theta = 0°$ or 180°. Any error in the initial estimate of plasma density, or Debye length, would not affect the algorithm for determining $I_e(0)$, α, kT_e, and n_e.

Finally, we briefly comment that the presence of a satellite may affect its local plasma density. Enhancement of local plasma density has been observed by *Olsen et al.* [1981], who attributed the cause to possible potential barriers due to differential charging on the satellite surface. In our case, electron beam emissions may also be plausible reasons. For purposes of designing better experiments for improved determination of Langmuir probe parameters for spacecraft and the parameters of the ambient plasma, we suggest emitting a high-energy (several keV) electron beam at night. High-energy beam would generate less electrons in the vicinity of the spacecraft. Without photoemission from the spacecraft, the Langmuir probe current at $\phi = 0$ reduces to $I_e(0)$ regardless of the geometry, sphere, or cylinder. This would determine the ambient current without extrapolation or the ambiguity factor μ between 1 and 1.1.

Appendix

This appendix discusses the differences in functional forms of Langmuir probe current due to spherical and cylindrical geometries. The flux J collected by a spherical probe is given by [*Mott-Smith and Langmuir*, 1926]

$$J = J_o\left(1 + \frac{e\phi}{kT}\right) \tag{14}$$

where J_o is the random flux $n_\infty(kT/2\pi m)^{1/2}$, n_∞ is the plasma density at infinity, and m is electron mass. The flux J is related to the current I by a multiplicative factor of surface area.

For a cylindrical probe, the flux J collected is given by [*Mott-Smith and Langmuir*, 1926; *Laframboise and Parker*, 1973]

$$J = J_o(2/\pi^{1/2})[\eta^{1/2} + g(\eta^{1/2})] \tag{15}$$

where

$$g(s) = \frac{1}{2}\pi^{1/2}\exp(s^2)\operatorname{erfc}(s)$$

$$= \exp(s^2)\int_s^\infty \exp(-t^2)\,dt \tag{16}$$

and

$$\eta = -\frac{e\phi}{kT} \geq 0 \tag{17}$$

For $s = 0$, $g(0) = \pi^{1/2}/2$. For large s, $g(s) \to 1/2s$, one approximates $g(\eta^{1/2})$ in (16) by $1/2\eta^{1/2}$, then approximates 1 + $1/2\eta$ by $(1 + \eta)^{1/2}$ and obtains

$$J \approx \left(\frac{n_\infty}{\pi}\right)\left(\frac{2kT}{m} - \frac{2e\phi}{m}\right)^{1/2} = J_o\left(\frac{2}{\pi^{1/2}}\right)(1 + \eta)^{1/2} \tag{18}$$

The functions $[\eta^{1/2} + g(\eta^{1/2})]$ and $(1 + \eta)^{1/2}$ versus η [*Mott-Smith and Langmuir*, 1926; *Swift and Schwar*, 1977] already show little difference for $e\phi > kT$ and no visible difference at all for $e\phi > 2kT$. This property further supports that our starting point of the data fitting (section 4.3) at about 30 eV (see Figure 7), below which the data deviate from the Langmuir probe form considered.

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